Angular Dependence of DRAM Upset Susceptibility and Implications for Testing and Analysis

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I – Introduction

The upset responses of various dynamic random access memories (DRAMs) have been studied previously, as they are becoming more prevalent in space missions [1-5]. Many different types of responses have been seen in these devices including single-bit upset, bit-line upset [6], single event functionality interrupt (SEFI) and stuck bits [7]. This paper investigates two angular dependencies of single-bit upset response to heavy ions in some typical DRAMs.

The usual way of testing devices involves hitting the device with multiple ion species and energies using several tilt angles, θ (angles relative to normal incidence), to increase effective LET. The ideal test matrix would include many ion species and energies at normal incidence. Because of accelerator facility and test cost limitations, upset data is usually taken for only a few ions at several tilt angles and is interpreted, as far as possible, using the "cosine law" for LET

$$LET_{effective} = LET_{incident}/\cos(\theta), \text{ where } \theta \text{ is the tilt angle.} \qquad (1)$$

Of course this is incorrect for steep tilt angles because $LET_{eff} \rightarrow \infty$ as $\theta \rightarrow 90°$. However, steep angles are difficult to obtain in practice [8], and the range limitations of the available accelerator ions would require large adjustments of the cross sections obtained anyway. In practice, tilt angles only up to about 60° are used to measure upset cross sections.

In space, ions are omnidirectional. The solid angle between normal incidence and 60°, front and back, is only half of the total. Upset rate calculations are lacking experimental data at large angles so the correct angular response must be incorporated via modeling into the rate calculation. The best that can be done is confirm that the tilt angle response used in the rate calculation agrees with the highest angle results in the data set, particularly in the threshold region between the threshold LET and the LET where the cross section "saturates."

Upset data collection and rate calculations typically ignore azimuth angle dependencies. The accuracy of the space upset rate calculations depend on assuming either (a) there is no azimuthal dependence or (b) the data is a reasonable average over all azimuthal angles.

In this paper data was taken using several ions at various tilt angles, as well as various azimuthal angles. For several fixed tilt angles between 0 and 66 degrees, the device was rotated in small steps over 360° of azimuth. Two device types, Oki MSM514400 4Mb DRAMs and Toshiba TC5165805AFT-50 64Mb DRAMs, were chosen; the former representative of current in-flight devices on JPL spacecraft and the latter representative of newer generation DRAMs.

II – Test Methodology

Testing was conducted using a special DRAM test board, and custom-built PCI-to-digital I/O board which allows testing of DRAMs at 160,000 addresses per second. The OKI devices were obtained from the Cassini flight lot, which were purchased as die and hermetically packaged. They required only lid and polyaimide removal as preparation for heavy ion testing. The Toshiba devices were commercial plastic-encapsulated parts that were completely disassembled and re-bonded for testing in order to eliminate interference from the lead frame.

Testing was done at Brookhaven National Laboratory with seven ion species: 56.3MeV lithium, 97.5MeV carbon, 141MeV fluorine, 186MeV silicon, 210MeV chlorine, 229MeV titanium, and 266MeV nickel. The range of normal incident nickel ions was 42.4μm and is the shortest of the selection. The devices were tested with a data pattern, known as "inverse bleed down," in which all bits were susceptible to upset[†].

This study focused on upsets of individual DRAM cells. Care was taken in the data collection and analysis to eliminate SEFIs and row or column hits. Multiple bit upsets (MBUs) where a single ion upsets more than one cell [9, 10] are ignored here, that is, they were counted as if they were independent upsets. That is the

[†] By exposing a DRAM die to a normal white light bulb for several minutes, the charge on the memory cells is drained-off enough to look like no charge is present (to the sense amps). This state of the device's cells is called the "bleed down" pattern, and is not susceptible to single-bit-upsets. The bit-wise inverse of this pattern is the "inverse bleed down" pattern.

customary test methodology for DRAMs concerning MBUs. This does not mean that MBUs are unlikely or unimportant; one can see from the device saturation cross section being larger than the die area that MBUs predominate. The full paper will address the issue of how important MBUs are in the unexpected angular responses that were found.

III – RESULTS

A. *Oki DRAM Results* – Data at various angles were taken on the Oki part whose lack of azimuthal dependence allowed for combining all the data from different azimuth angles into single cross sections. This data is plotted in Figure 1 and assumes the cosine law holds (see Eq. 1). The ions at normal incidence are left hollow to allow the eye some interpretation. The graph deviates from the normal incidence trend in the threshold to saturation region.

It is clear from Fig. 1 that the lighter ions in the threshold region do not have more "effective LET" at angle as predicted by Eq. 1. A better approximation to this data is obtained if the response is modeled as isotropic,

$$LET_{effective} = LET_{incident}, \text{ for all } \theta.$$

Figure 2 shows this result, which is equivalent to a spherical charge collection volume and can be approximated as a cube in the RPP model.

This analysis leads to several ways of calculating upset rates: (1) assuming that Eq. 1 works up to tilt angles of 85°, (2) applying the standard RPP model with the 'A' parameter set at 5, (3) applying RPP with a cubic charge collection volume, or (4) assuming it is spherical. The results of using these methods are shown in Table 1. Failure to take enough data to recognize the tilt angle dependence changes the calculated interplanetary (or geosynchronous orbit) rate significantly (also note the isotropic and cube RPP rates differ by only 4%).

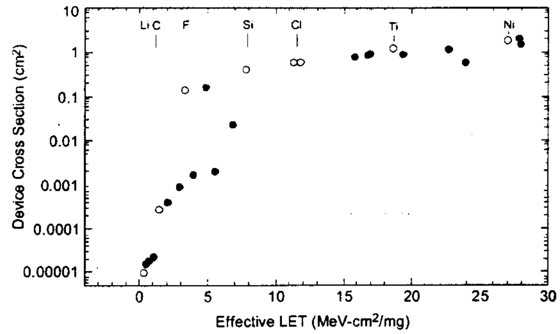

Figure 1. The cross section data for the Oki DRAM does not follow the "effective LET" model very well. Note the statistical error bars are smaller than the size of the plotting symbols. Also, hollow symbols are normal incident ions.

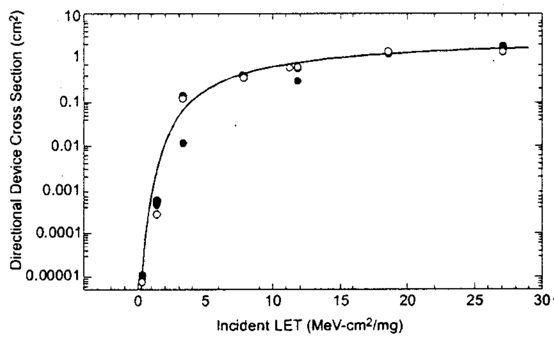

Figure 2. An isotropic model of the Oki response at different tilt angles yields a much better fit.

Table 1. Comparison of Calculated Oki SEU Rates (#/device day)

Eq. 1 to 85°	Usual RPP (A=5)	Cube RPP	Isotropic
21	15	5.5	5.3

B. *Toshiba DRAM Results* – The Toshiba's angular response is more complicated than the Oki's. We observed an extreme variation in cross section with azimuthal angle for the lower LET ions at moderate tilt angles. Figure 3 shows an example where the device was struck with fluorine at a 48° tilt angle along azimuthal angles in increments of 15°. Note the factor of ~100 difference between 0° (or 180°) and 90° (or 360°). Other tilt angles and other low LET ions also show the response is strongly dependent on azimuthal angle.

It is illustrative to consider the different results that would be obtained if tests were done at only one azimuthal angle. Figures 4 and 5 show cross section versus LET data taken at two azimuthal angles (as indicated in the insets – one along the long-axis the other along the short-axis). From Figure 4, one would conclude that Eq. 1 is working well and miscalculate the GCR upset rate by over a factor of 10 (exact values will be in the full paper). Figure 5 signals a tilt-angle problem. Note the similarity to Figure 1; however, removing the "cosine" dependence, as was done in figure 2, does not collapse to a smooth function. Either

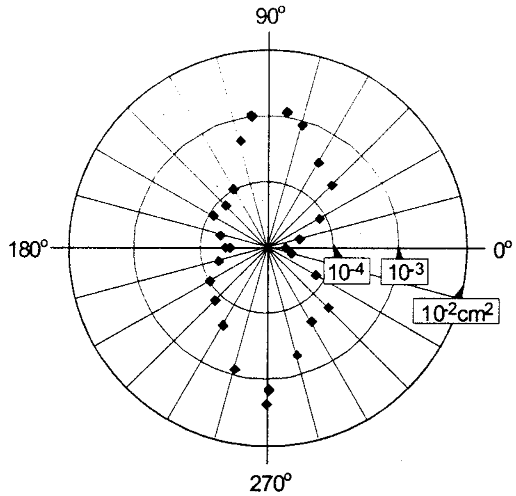

Figure 3. Cross section vs. azimuthal angle for the 64Mb Toshiba DRAM irradiated with 141MeV fluorine at a 48° tilt angle presented in polar coordinates. Error bars are 10% or better.

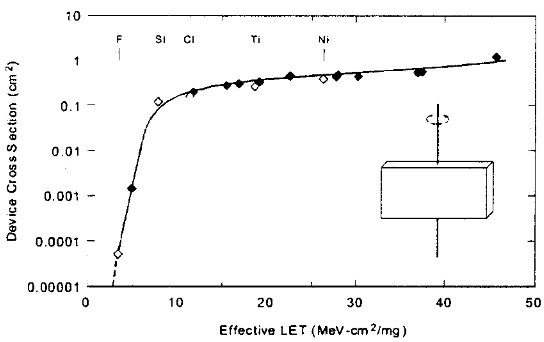

Figure 4. For this choice of azimuthal angle, cross section vs. effective LET looks good, but this is an illusion that will lead to an order of magnitude high SEU rate calculation. (Error bars are less than 10%)

orientation results in serious SEU rate error.

IV – Discussion

A. *Modeling* – Proponents of the RPP model [11] of charge collection will likely conclude that only one additional parameter is needed to fit the azimuthal dependence of the Toshiba device, perhaps breaking the sensitive area into length and width [12]. Additional difficulty comes in the fact that both fluorine (LET = 3.36) and silicon (LET = 7.88) show the cross section to vary by a factor of ~100 when the azimuth angle is varied from 0° to 90° (with a constant $\theta = 48°$). Two tentative ways in which the RPP model might explain this each lead to problems. One tentative explanation is that the RPP has a 100 to 1 (or otherwise very large) aspect ratio, which doesn't match the known cell size. Another tentative explanation is that the aspect ratio is more like 2.5 to 1 (as suggested by the device physical layout), but the smaller cross section is very close to threshold conditions for that ion direction. This could

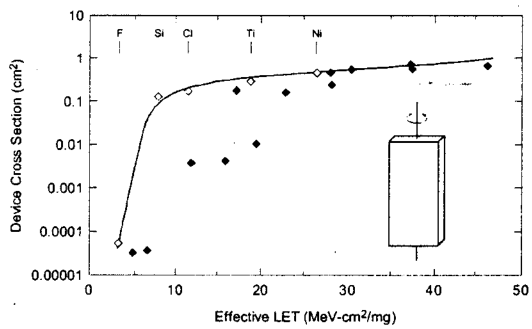

Figure 5. This alternate choice of azimuthal angle yields a messy cross section vs. effective LET, signaling a tilt-angle dependence problem, but still allowing one to miss the strong azimuthal dependence.

explain the large cross section ratio for one of the ion types but not both because they will not both be so precisely close to threshold conditions.

Another problem with the RPP model is based on physics. The model assumes that all charge liberated at a given location is collected at a single node, or not collected at all (the charge-collection efficiency assigned to a given node and evaluated at a given location is either 0 or 1). In reality, some of the charge can be collected at one node, and another part of the charge can be collected at another node (the charge-collection efficiency can be a fraction). This is known to be true because multiple-bit-upsets can occur at normal incidence. We believe that charge sharing among the active nodes of the type analyzed by Edmonds in [13] is more realistic and accounts for both the azimuthal dependence and the reverse tilt angle (where the cross section goes down with tilt angle) effects sometimes seen at low LETs [14].

B. *Testing* – In order to calculate realistic space upset rates, one must make additional measurements to investigate azimuthal angle effects. In particular, for unusual tilt angle dependencies, more normal incident ions must be used to obtain the same quality cross section versus LET information obtained if the effective LET model worked. Azimuthal dependencies should be checked at LET's near threshold using 0° (or 180°) and 270° (or 90°) for fixed tilt. If found a large data set is required, at least until a community-accepted model of the azimuthal dependence is developed.

V – Conclusion

These results show that the angular response of DRAM upsets can be more complicated than previously thought. The large azimuthal response has not been reported previously. It is important to measure, in detail, how the upset susceptibility varies with tilt angle and, at least, to check the assumption of azimuthal angle invariance. Devices like the 64Mb Toshiba DRAMs, which violate that assumption require detailed measurements of at least one quadrant (0-90°) of azimuth angle. Further, it is unlikely that adding a parameter to the RPP model is sufficient to approximate the Toshiba angular responses. Thus (for the two types of DRAMs of this study) detailed angular data and appropriate upset calculations are needed to obtain even order-of-magnitude upset rates (though for the Oki, only the tilt angle dependence needed careful consideration). The full paper will discuss the extent to which these DRAM results might apply to other memory types in the future, particularly highly-scaled SRAMs.

VI – References

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Angular Dependence of DRAM Upset Susceptibility and Implications for Testing and Analysis

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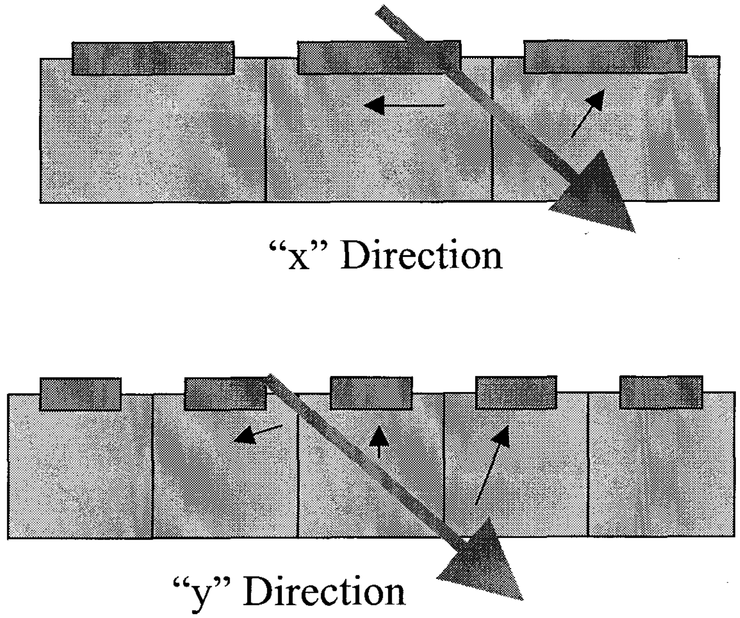
Work Performed under contract with the National Aeronautics and Space Administration

Contents

- Background to Investigation
- Test Method - as initially carried out
- Unexpected Discovery
- Modeling Thoughts and Difficulties
- Need for some sort of standard test method
- Key Points

Azimuthal Dependence Background

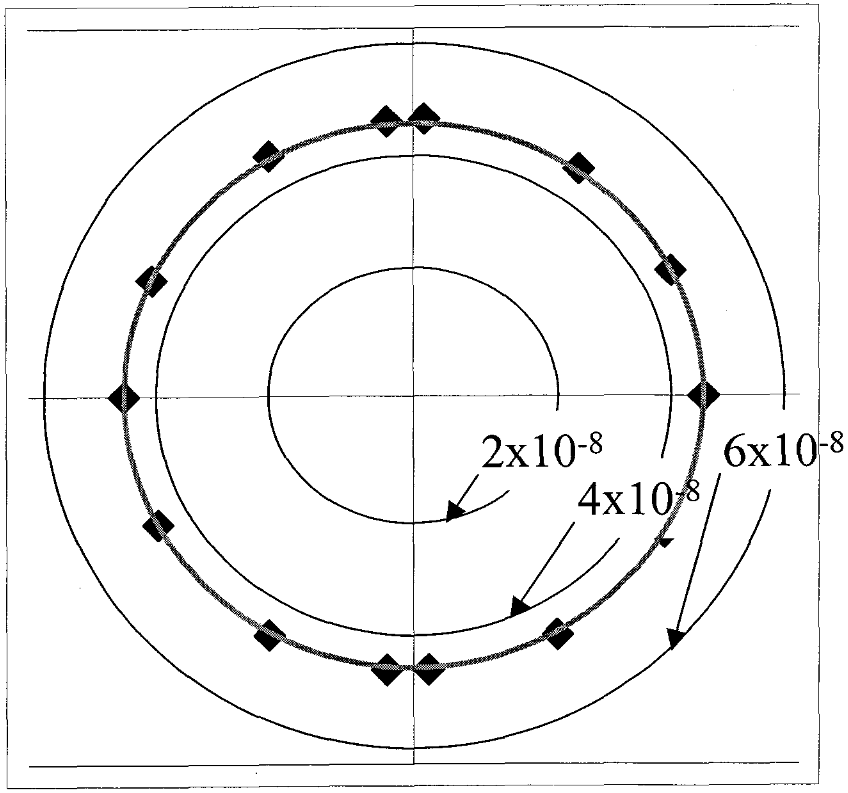
- **DRAMs don't typically have an aspect ratio of 1**
- **High densities mean close packing**
  - $1 cm^2$ of die / 64 million bits = $15 \mu m^2$
- **Deep charge collections regions (~10μm)**
- **Reasonable to assume the aspect ratio of the cell is similar to the aspect ratio of the charge collection region**
- **Higher cross sections expected due to MBUs**



Similar ion strikes produce charge in more cells in direction "y" than in direction "x."

Test Methodology

- **Two candidate devices have been thoroughly tested**
  - Oki 4Mb
  - Toshiba 64 Mb
- **Devices were tested with a random pattern for full electrical check-out**
- **DRAMs are upsettable in only one configuration**
- **With high LETs the devices were irradiated at tilt angles up to 65° while rotating the devices through several azimuth angles.**
- **Sample plot with no azimuthal dependence shown**



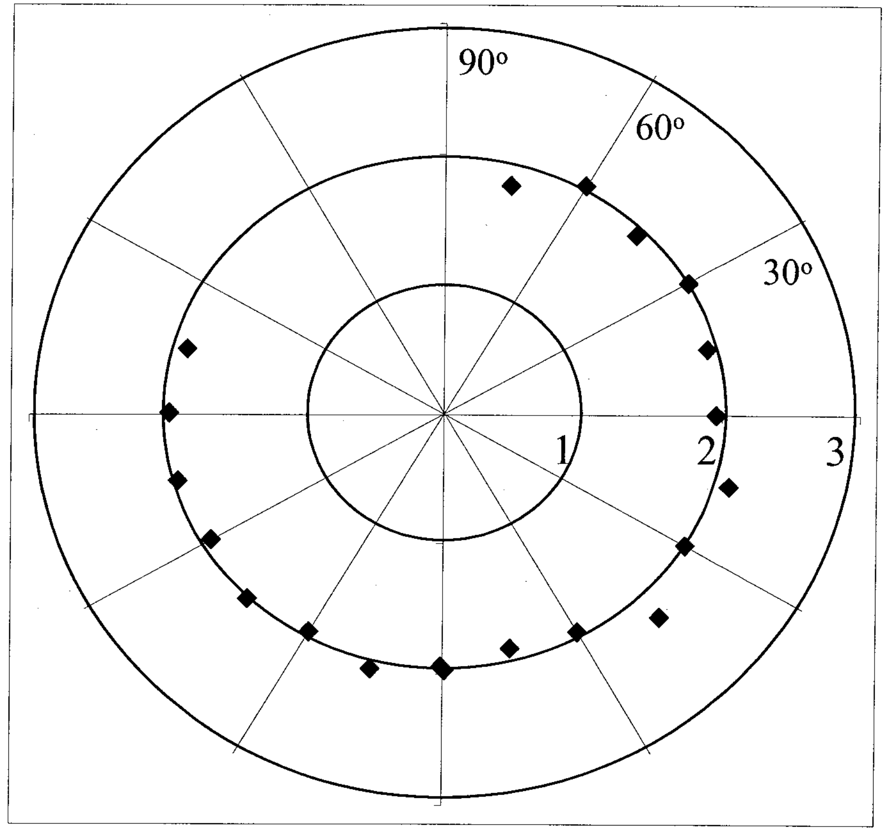
A sample radial plot for a device that has no azimuthal dependence. Note the cross section would be $4.6 \times 10^{-8} cm^2$

Obtaining Good DRAM Data

- **DRAMs have several upset modes that can get into upset data**
  - Single cell upsets
  - Row hits
  - Single event functionality interrupts (SEFIs)
  - Multiple bit upset
- **Ruling out everything except single and multiple bit upsets**
  - All of these events involve multiple upsets in one address
  - Devices are tested twice with the same conditions when possible
  - Errors per run are kept low
- **Multiple bit upset**
  - Important for the questions initially asked, but not for the azimuthal dependence found

Oki Results

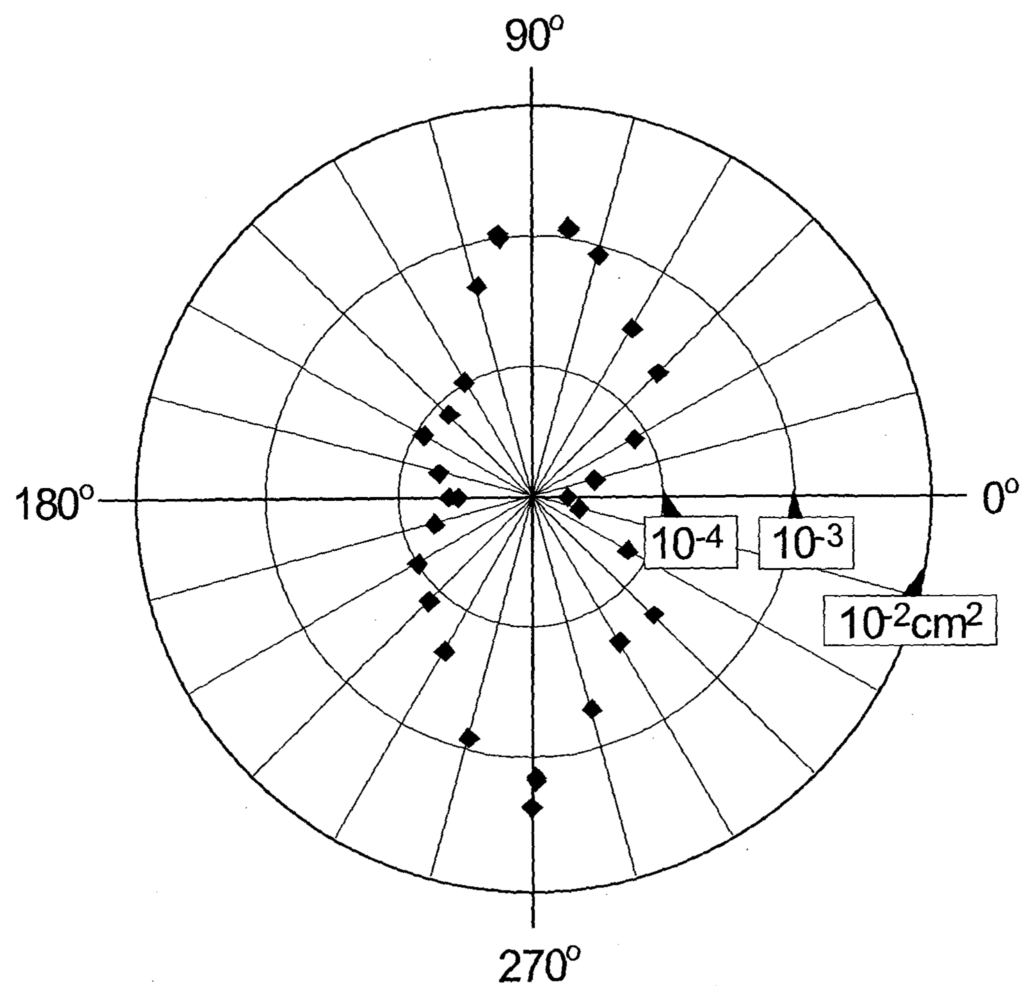
- **Oki devices showed almost no azimuthal dependence**
- **Sample plot for the Oki device is shown at the right.**



Plot of cross section vs. azimuth angle for Okis irradiated with 18.7 incident LET Ti and tilt angle = 60°. Note the cross section is about 2cm^2 for all azimuth angles.

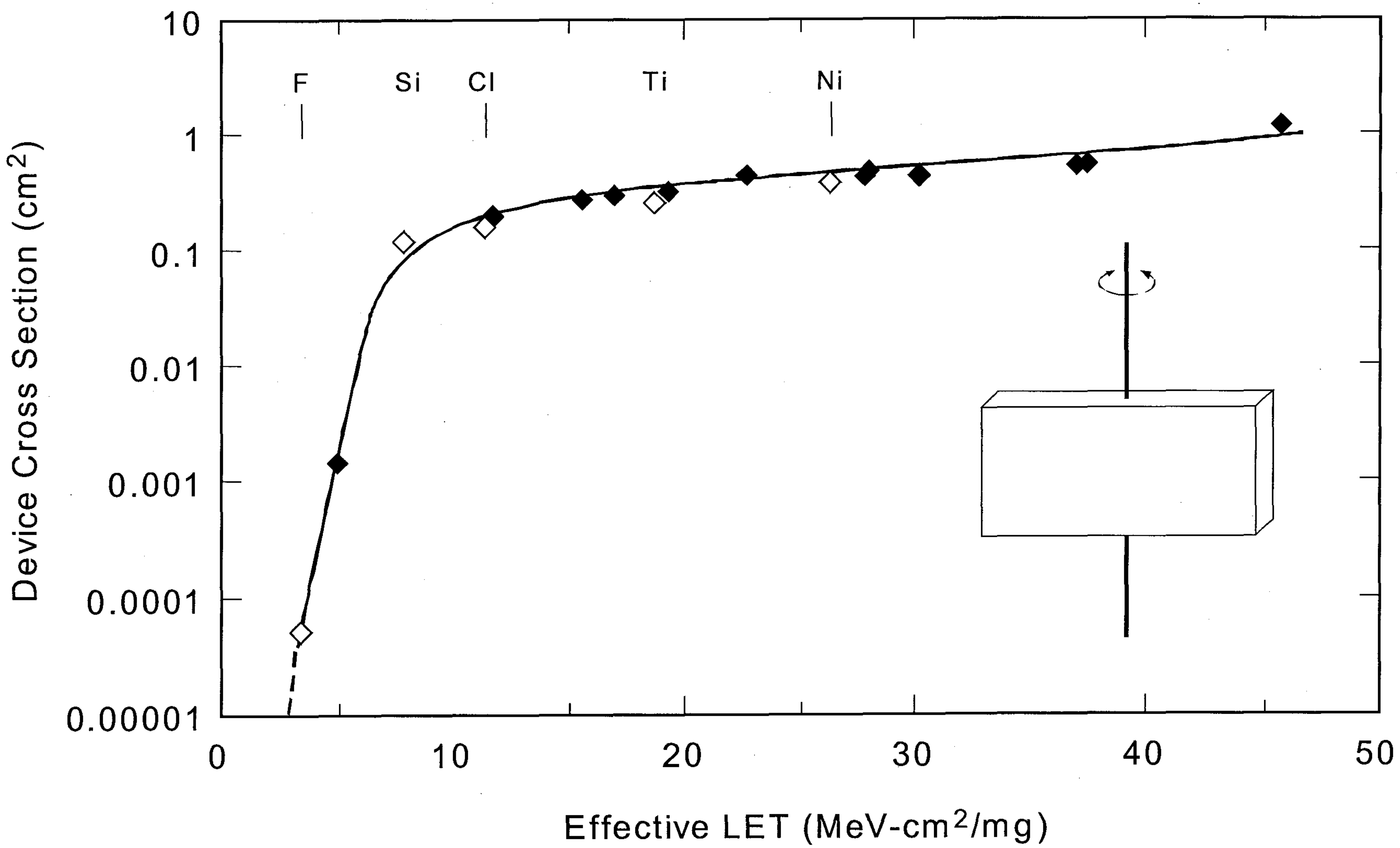
Unexpected Discovery

- **Much stronger dependence on azimuth found on one device - The Toshiba 64Mb**
- **Difference was orders of magnitude**
  - Not what would be expected of physical device geometry - rules out geometrical charge collection issues
- **This effect seemed more interesting than the original plan**
  - Increased interest in the threshold region

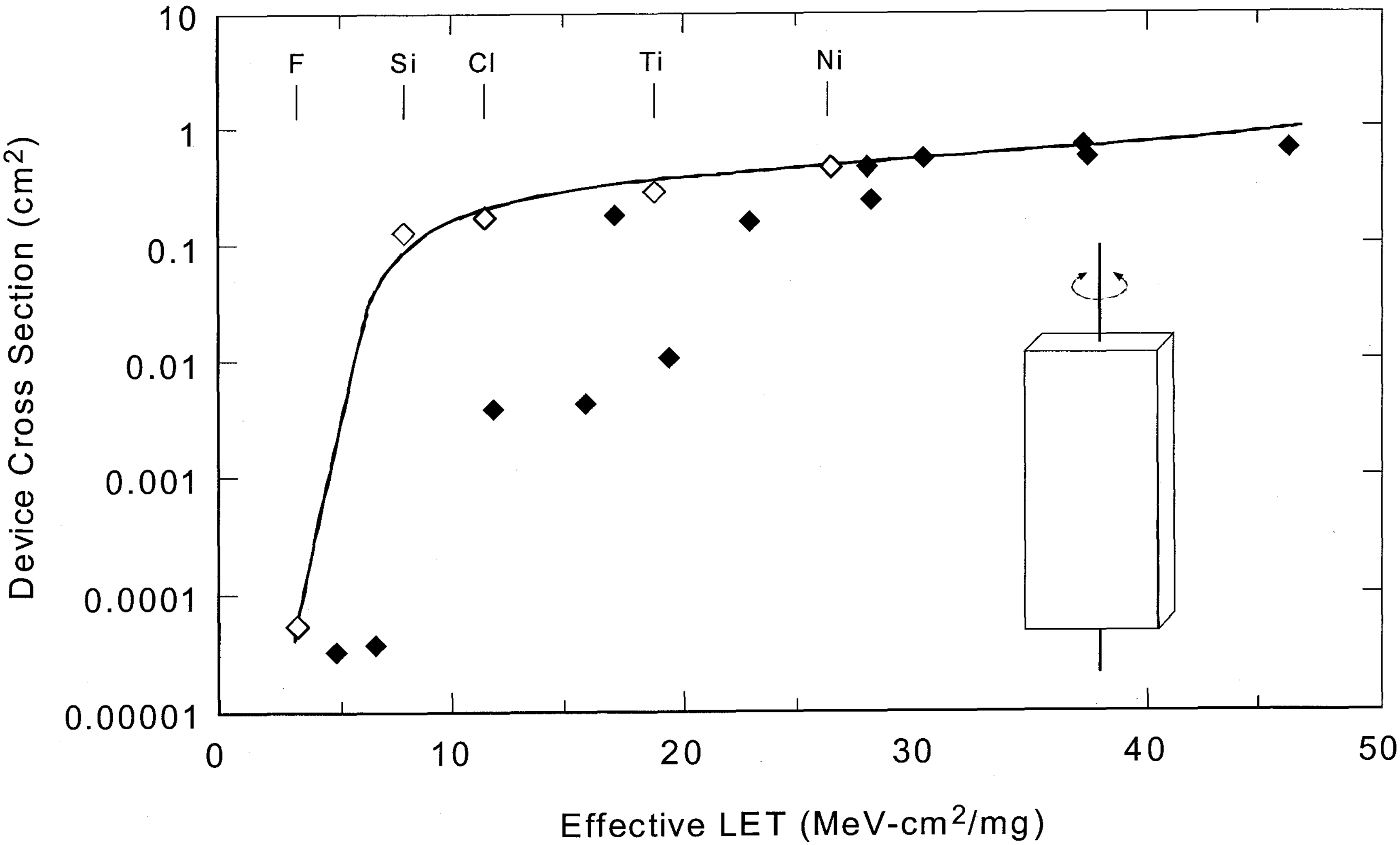


Azimuthal Dependence of Toshiba 64Mb DRAMs to 3.4 incident LET Fluorine at a tilt angle of 48°

Toshiba 90° Azimuthal Results

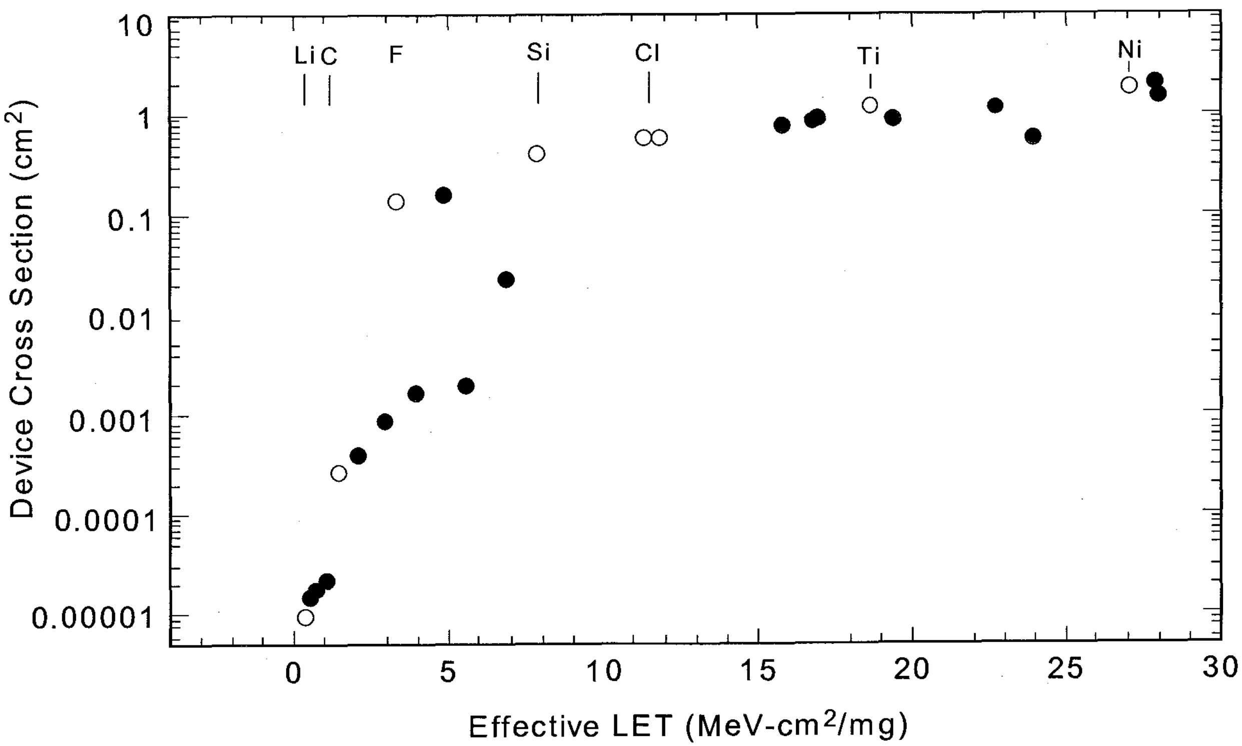


Toshiba 0° Azimuthal Results



Tilt Dependence Note

- The cosine law is known not hold for large angles
- The interesting question is what tilt angle does it break down at?
- For the Okis the answer is "all of them."



This figure shows how strange the Oki results are when plotted the traditional way

Normal incident ions are plotted with open circles

Key Points

- Looked for Azimuthal Dependence but found more than expected
- Examined devices that have unusual tilt and azimuthal angle dependencies
- The data presented suggest that accurate upset rate calculations require lots of data covering the angular possibilities
- We have a model for the tilt dependence
- We are looking for a model that can explain the azimuthal dependence seen
- Still remains to determine the Multi-Bit effect of large LET ions on DRAMs